Airborne Multispectral Scanner Data for Evaluating Bottom Sediment Types and Water Depths of the St. Marys River, Michigan

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ABSTRACT: Airborne multispectral data and models of the light interaction with water were employed for general assessment of river bottom soil types and water depths in the study area. This required analyses of scanner data using multivariate pattern recognition techniques. Subsequent radiometric modeling and analyses of field data resulted in determination of class identities and creation of bottom type and water depth thematic maps from scanner data. Accuracy assessments indicated that the effort produced very good identification of five general bottom sediment types (85 percent) and general water depths (95 percent).

INTRODUCTION

LARGE ENGINEERING PROJECTS often require environmental analyses and production of environmental impact statements (EIS). One portion of this effort is the assessment of impacts of a project or action on environmental resources such as wetlands, wildlife, and fisheries. Evaluations of these resources are expensive using traditional measurement techniques. The resources vary in space and in time and it is difficult to sample their variability. As a result, increased attention has been focused on advanced technologies to evaluate resource characteristics on a per-area basis. Technologies such as remote sensing can provide area-wide information and a potentially unique source of data for analyses of environmental resources.

The Detroit District Corps of Engineers of the U.S. Army (USACE) is charged with operation and maintenance of the locks at Sault Ste. Marie, Michigan. They are concerned with the environmental resources, their natural variability, and any potential affects of lock operation and navigation on the St. Marys River and Lake Superior system (USACE, 1979; USACE, 1988). The locks and St. Marys River receive a large volume of iron ore, coal, and wheat, and transport of these bulk and other cargoes is critical to the regional and national economy.

The importance of environmental resources in the St. Marys River area has also been recognized, and the government and a number of groups have many questions that must be answered. Hence, there is a continuing need to evaluate environmental resources in the St. Marys River as they are influenced by federal actions or projects. This need for information is mandated by the National Environmental Policy Act (NEPA), the Fish and Wildlife Coordination Act, and other laws and regulations.

The large size of the river system, extreme weather, and rural surroundings make data acquisition difficult and expensive. Remote sensing and aerial photography were initially proposed to supply a variety of data to augment other point measurements. The value of remote sensing was inherent in its capability to provide data over large areas, and to measure spectral and spatial variables that are ordinarily unavailable from traditional sampling methods.

Studies have demonstrated a unique capability to measure aquatic and water resource variables using combined remote sensing and field sampling experiments (Klemas *et al.*, 1974; Lathrop and Lillesand, 1986; Lyon *et al.*, 1988). To further the application of remote sensor data for measurement and modeling of water resources requires efforts to employ deterministic models in addition to the statistical approaches which have been so successful. Radiation Transfer (RT) models have the potential to simulate various water resources, and also to fulfill the need for a deterministic model based on physical and/or chemical processes (Scherz and Van Domelen, 1975; Weidmark *et al.*, 1981; Butkata *et al.*, 1983; Suits, 1984; Hollinger *et al.*, 1985; Bukata *et al.*, 1988). It remained to develop a simple RT model for the St. Marys River, and to determine the accuracy of this combined remote sensor data and deterministic modeling approach to develop bottom type and water depth map products for use in environmental analyses.

METHODS

A variety of methods were combined to develop the final products and test their accuracy. These efforts included the acquisition of remote sensor data and the processing of the data into thematic maps of bottom types and water depths, as well as an independent accuracy assessment of the quality of the maps.

AIRBORNE SCANNER DATA

The need for a detailed spectral and spatial data set was met by use of multispectral remote sensor data. The U.S. Environmental Protection Agency (EPA) made an aerial overflight of the St. Marys River study area on 19 October 1985 during very good weather conditions. The exact configuration of the sensor flown by the EPA Environmental Monitoring Systems Laboratory in Las Vegas, Nevada was a Daedalus 1260 scanner that acquired data in 12 spectral windows or bands from 0.38 to 14.00 µm, with a 10-m resolution element or pixel. 1:24,000-scale color aerial photographs were also taken with a Wild RC-8 camera. Concurrently, water variables were sampled in the field by boat at 36 stations. Data included total suspended solids, Secchi Disk depth, temperature, chlorophyll *a*, and depth to bottom.

The EPA Laboratory processed the raw aircraft scanner data, including unpacking the data from high density format into a computer compatible density of 1600 BPI. They also made ra-

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diometric calibrations, corrections of scan angle distortions, and preliminary geometric corrections of any pixel size distortion due to aircraft yaw, pitch, and roll.

The processed scanner data were then used to generate both image and computer categorization products. Data analysis required two general steps. The first step included geometric corrections, selection of a sub-set of spectral bands for analysis (feature selection), and statistical pattern recognition (Moik, 1980) of water colorants classes. Resulting products were a database of bottom sediment types and water depth classes ready for subsequent analyses in step two of the methods presented here (Hollinger *et al.*, 1985).

The second step focused on development of bottom type and water depth thematic maps. The approach employed Secchi Disk measurements, water class statistics from categorization, and the RT model for calculating the spectral radiance or brightness from the water column and bottom (Scherz and van Domelen 1975). The simple RT model estimated incoming light condition and fore- and backscattering of light in the water column, and was used to relate the contributions of varying water depths to the resulting brightness values measured by a remote sensor. Elements of this approach are consistent with more complex approaches for deterministic modeling of water depth and water quality (Bukata *et al.*, 1978; Jain *et al.*, 1981; Philpot, 1981; Bukata *et al.*, 1983; Suits, 1984; Hollinger *et al.*, 1985).

Step 1: Identification of Bottom Types

The first objective was to identify the general bottom sediment types in the study area. This was necessary for the second objective as well, because different bottom types commonly exhibit great differences in reflectance. For example, sand substrates tend to have higher reflectances than silt, clay, or organic soil materials. These differences can result in incorrect determinations of water depth, and it was necessary to separate or stratify our data into bottom type classes. As a result, determination of water depths for each bottom type class or stratum could be made in a direct manner (Weidmark *et al.*, 1981).

In the Lake Nicolet portion of the St Marys River there were several distinct bottom sediment types. These included the following river bottom sediment categories or types: sand, silt/clay and silt/sand combinations, and sand/silt and sand-rock/silt combinations. Each bottom type exhibited distinct spectral reflectance in several spectral data bands, and they could be discriminated spectrally. Hence, unsupervised computer categorizations or pattern recognition experiments were employed to separate bottom types, and thus achieved stratification of classes by bottom type to allow water depth analyses to be completed as a separate effort (Jain *et al.*, 1981; Weidmark *et al.*, 1981).

Several procedures were followed to develop the desired thematic map products. Initially, a feature selection experiment identified an optimal subset of the 12 bands for processing (Moik 1980). Daedalus 1260 bands 1 (0.38 to 0.42 μm) and 2 (0.42 to 0.45 μm) were eliminated due to atmospheric and/or water opaqueness at short, visible wavelengths. Bands 9 (0.80 to 0.89 μm) and 10 (0.92 to 1.10 μm) were also eliminated due to sensor anomalies. The bands mentioned here were also eliminated because they supplied little or no detail on water resources useful for this analysis.

The remaining six bands were used in the experiment. Bands 3, 4, and 5 (0.45 to 0.50, 0.50 to 0.55, and 0.55 to 0.60 μm) provided data for bottom type categorizations and measurement of water depths. Band 6 (0.60 to 0.65 μm) was valuable for identification of shallow water areas and their depth conditions. Near and thermal infrared channels 7 and 11 (0.65 to 0.69 and 8.00 to 14.00 μm) were used to identify upland classes in the scanner scene, and to separate them from the water resource classes of interest.

As a first step, upland or terrestrial areas in the scene were "masked out" or removed from the analysis. The goal was to reduce the size of the data set by eliminating data unimportant to the project. It also reduced the contribution of spectrally distinct terrestrial data to this spectrally based pattern recognition experiment aimed at identifying aquatic resources. To do this, a two-band data set was copied from the original; it consisted of near and thermal infrared bands 7 and 11. This two-band scene was categorized by clustering, six land and water categories were selected a priori, and a thematic map of terrestrial and aquatic resources was made. All terrestrial spectral classes were subsequently recorded to class zero, and all aquatic spectral categories were recoded to class one. The original four-band image was multiplied by the resulting terrestrial/aquatic image of "1s" and "0s." The result was a scene composed of only areas of the water resource classes of interest.

The data set used in categorizations was this "masked" four-band scene described above. Preliminary categorizations on a smaller area indicated that a clustering algorithm with 50-classes yielded the best product. In addition, a minimum cluster distance of two was determined to optimize the recognition of bottom types. Categorizations were completed using these conditions and the clustering algorithm of the ERDAS system.

The final categorized products required geometric corrections. To correct the geometry, Ground Control Points (GCPs) were selected from road intersections, aids to navigation, and other distinct points on both maps and image products. GCPs were digitized from 1:24,000-scale USGS maps and referenced in UTM coordinates. The row and column indices of GCPs were taken from coordinates of the scanner data, and were compared to UTM coordinates in the transformation. A root-mean-square (RMS) error of 5 was achieved with a cubic-convolution algorithm (Moik, 1980).

Final products were made from the geometric corrected, categorized scanner data images. The resulting products included model determinations and maps of general bottom type and water depth. The individual spectral classes selected by clustering ($n = 50$) were identified as to bottom type. Classes were assigned or stratified into a bottom type class by a combination of approaches, including (a) evaluation of field data, (b) interpretation of the color photographs from the overflight, (c) aerial photos from other dates, and (d) two-axes graphical plots of cluster means for each class. Resultant images displayed the location of sand, combinations of silt/clay and silt/sand, and combinations of sand/silt and sand-rock/silt types.

Water quality data were acquired during the overflight, and samples exhibited the oligotrophic quality characteristics of the Lake Superior headwaters. In the study area, localized concentrations of suspended solids were less than 1.0 mg/l and no higher than 3.0 mg/l, and chlorophyll *a* was approximately 0.3 mg/l. Due to these low concentrations, it was assumed that their contributions to remote measurements were small and probably would not alter the results. Hence, it was deemed unnecessary to model these water quality characteristics for this particular overflight.

Step 2: Water Depth Determination

The modeling effort employed on-site Secchi Disk measurements to estimate the extinction or attenuation of light by the water column. The extinction coefficient of water was estimated using Beer's Law and approximations made by Scherz *et al.*, (1974). The basic assumption was that the energy returned by the Secchi Disk to the observer in a boat was approximately 10 percent of the initial radiance on the water surface (Scherz *et al.*, 1974). From this assumption, it followed that we could calculate

$$L \text{ (radiance on Secchi Disk, } Ysd) = L\text{(radiance initially under the water surface)} / e^{aY},$$

where a is the extinction coefficient and Y is the depth of water. As the energy reaching the Secchi Disk (sd) at depth "Ysd" is approximately 10 percent of L (at the water surface), the extinction coefficient (a) can be calculated. It follows that

$$e^{aYsd} = L(\text{surface}) / LYsd = 1/0.10 = 10.0$$

Rearranging the equation results in a solution:

$$aYsd = 2.3,$$
$$a = 2.3/Ysd$$

The Ysd measured during the overflight was 10 ft (3m). The resulting extinction coefficient was calculated as $a = 2.3/10.0$ or 0.23. This extinction coefficient value was within the range observed by other investigators in the same or similar waters (Bukata *et al.*, 1978, 1983; Liston *et al.*, 1986).

Once the extinction coefficient was established, the RT model was used to calculate the radiance of the water column. The model incorporated the fore- and backscattering and extinction of light in uniform layers of depth, the bottom reflectance, and suspended and dissolved substance influences on radiance. These components were addressed by modeling the attenuation of light with depth as a series of five layers (Scherz and Van Domelen, 1975; Scherz *et al.*, 1977; Suits, 1982). Each layer of equal depth or thickness was characterized by a separate calculation of the contribution of light from fore- and backscattering and extinction of light by water. The results were used to develop a "lookup table" of brightness values for the five water depth classes for each bottom type.

The entries in each lookup table consisted of five brightness values that may be expected for each given depth, 1/5 Ysd or 2 ft (0.8m). The model calculated the percentage of each layer's contribution and was used to determine the light that would be measured from a given depth. Individual lookup table entries for a certain depth range were calculated from

$L(Y \text{ at } "i") = [L \text{ (shallow water)} - L \text{ (deep water)}]$ (proportion of light returned from layer "i").

Contributions of light from these depth layers were calculated by Scherz and Van Domelen (1975) and Scherz *et al.* (1977) using the relationship

$$L_{Yi} = L \text{ (incident) } t^{(2i-2)} F^{(2i-3)}$$

where L_{Yi} is the radiance from a given layer "Y," "t" is the transmission of light through a layer, F is the combination of unit backscatter that the light will experience, and "i" is the given layer of thickness "Y."

Using this approach, Scherz *et al.* (1977) determined that clear water will return radiance approximately in the proportion of 0.590 or 59.0 percent of the incident radiance from the first layer, 24.0 percent from the second, 9.5 percent from the third, 7.1 percent from the fourth, and 0.4 percent from the fifth layer of water. The depth or thickness of each layer is again 1/5 of the Secchi Disk depth. For this analysis we assumed BV $\cong$ L(sensor). This is a suitable assumption due to (a) the small study area and low altitude overflight, (b) the early morning and clear atmospheric conditions during the overflight, and (c) the uniform conditions of path radiance would presumably contribute uniformly to the L(sensor).

The BV data from a given bottom type and its classes were searched to identify "shallow water" and "deep water" examples. The mean BV data in the four bands were used to identify the high and low BV and supply a range. The proportions from the Secchi Disk calculations were used to identify the portion of the BV range that represented the water depths we sought to identify. The BV in each band, for each water depth class (2.0 to 4.0, 4.0 to 6.0, 6.0 to 8.0, >8.0, and >10.0), was calculated and "stored" in a lookup table.

The above calculations allowed us to determine the brightness values (BV) associated with different depths of water over the same bottom type. By selecting a very shallow or high BV example, and a very deep or low BV example of each bottom type, we were able to develop a lookup table consisting of mean brightness values for each bottom type from the four spectral bands. The resulting lookup tables were used to assign general depth classes in 2-ft increments (0.8m) to 10 ft (3m) for each class in the categorized scanner scene.

The final product was developed from (a) look-up tables and use of (b) field sampling data from the overflight, sampling data from 1987, and sampling data from other studies (Liston and McNabb, 1983).

The look-up table also incorporated a correction for the actual water depth calculated. The final product needed to be in low water datum (LWD), as were NOAA charts, to allow comparison. This was completed by subtracting the difference of the actual water level during overflight and the LWD.

To verify the quality of the bottom type and water depth thematic maps, an accuracy assessment was completed. In August, 1987, 137 bottom samples and water depths were collected during a three-day period in the St. Marys River area. Ninety-seven of the bottom samples were submitted to the USACE soils laboratory in Cincinnati, Ohio and soil types of the bottom samples were measured by feel. Seventy-four of these soil and 76 of the depth samples were taken in the Lake Nicolet study area.

RESULTS AND DISCUSSION

A combination of techniques – including unsupervised categorization of scanner data, use of a radiometric model, and field data analysis – yielded thematic maps of general bottom soil type and water depth (Plates 1 and 2). These products compared well to field sampling data (Figures 1 and 2). Verification of the accuracy of bottom types was performed with sampling data from the 1987 field season (USACE, 1989). Class accuracies are presented in Table 1. The total accuracy was 63/74 samples or 85 percent.

Verification of water depths was completed by comparing, point by point, selected areas of (a) the USACE water depth maps and (b) samples from the 1987 field data collection for verification. The individual class accuracies are recorded in Table 2. The total accuracy was 72/76 samples or 95 percent.

These results were partially due to the very low concentrations of water colorants in the Lake Superior headwaters of the St. Marys River (Bukata *et al.*, 1978; Bukata *et al.*, 1988). Absence of water colorants made this a valid approach, and others have experienced similar results (Lathrop, 1988; Hutchinson, 1989). The same results would not be possible in waters containing concentrated phytoplankton or suspended sediments.

The remote sensor approach may be valuable for several types of environmental analyses. The resulting thematic maps of water depths and bottom types over large areas can supply data that are difficult and much more expensive to obtain as compared to products resulting from other technologies. The combination of limited field sampling and remote sensor data potentially could supply similar information in other clear water areas.

CONCLUSIONS

In the St. Marys River, the use of a combination of categorized airborne scanner, radiometric, and field data yielded thematic maps of water depths and bottom types. The approach used here, of identifying the individual contribution of bottom sediment types and stratifying the data set by bottom type and then determining the brightness value of water depths, allowed for accurate measurements. This combination of remote sensing measures and modeling was very useful in meeting requirements for information to evaluate the characteristics of environmental resources.

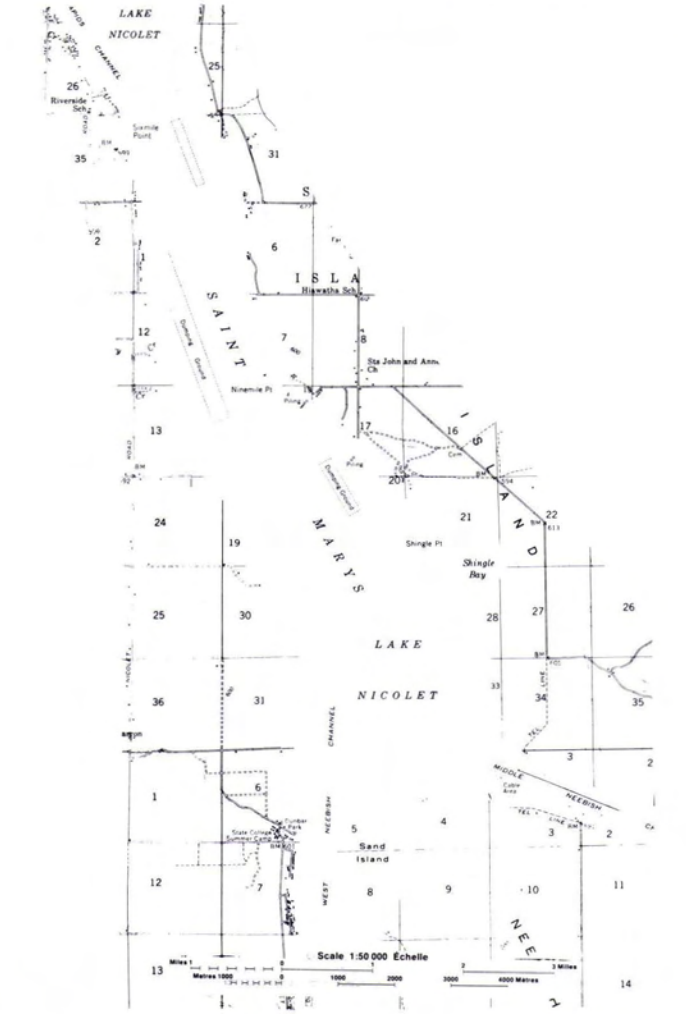

FIG. 1. Location map for the St. Marys River and Lake Nicolet, Michigan study area.

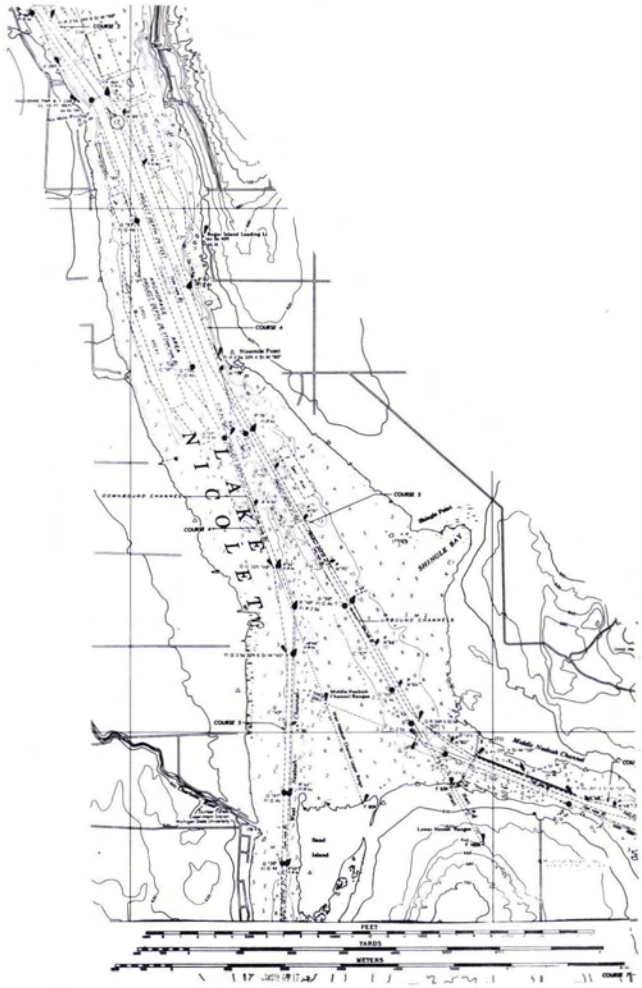

FIG. 2. NOAA chart of the study area. This is the same area presented in Plates 1 and 2.

TABLE 1 CLASS ACCURACIES OF THE REMOTE SENSOR DERIVED BOTTOM CATEGORIES AND THE SAME CATEGORIES IDENTIFIED IN THE FIELD

Derived Categories	Remote Sensor Derived Thematic Map Categories				
	Sand	Silt/Clay	Silt/Sand	Sand/Silt	Sand-Rock/ Silt
Sand	18/21, 85%				
Silt/Clay		9/14, 64%			
Silt/Sand		5/14, 36%	12/13, 92%	1/11, 9%	
Sand/Silt	3/21, 15%		1/13, 8%	10/11, 91%	3/15, 25%
Sand-Rock/ Silt					12/15, 75%

TABLE 2 CLASS ACCURACIES OF THE REMOTE SENSOR DERIVED WATER DEPTH CATEGORIES AND THE SAME CATEGORIES IDENTIFIED IN THE FIELD

	2.0-4.0 ft	4.0-6.0 ft	6.0-8.0 ft	>8.0 ft	>10.0 ft
2.0-4.0 ft	5/6, 83%				
4.0-6.0 ft	1/6, 17%	12/13, 92%			
6.0-8.0 ft		1/13, 8%	17/17, 100%	1/17, 6%	
>8.0 ft				16/17, 94%	1/23, 4%
>10.0 ft					22/23, 96%

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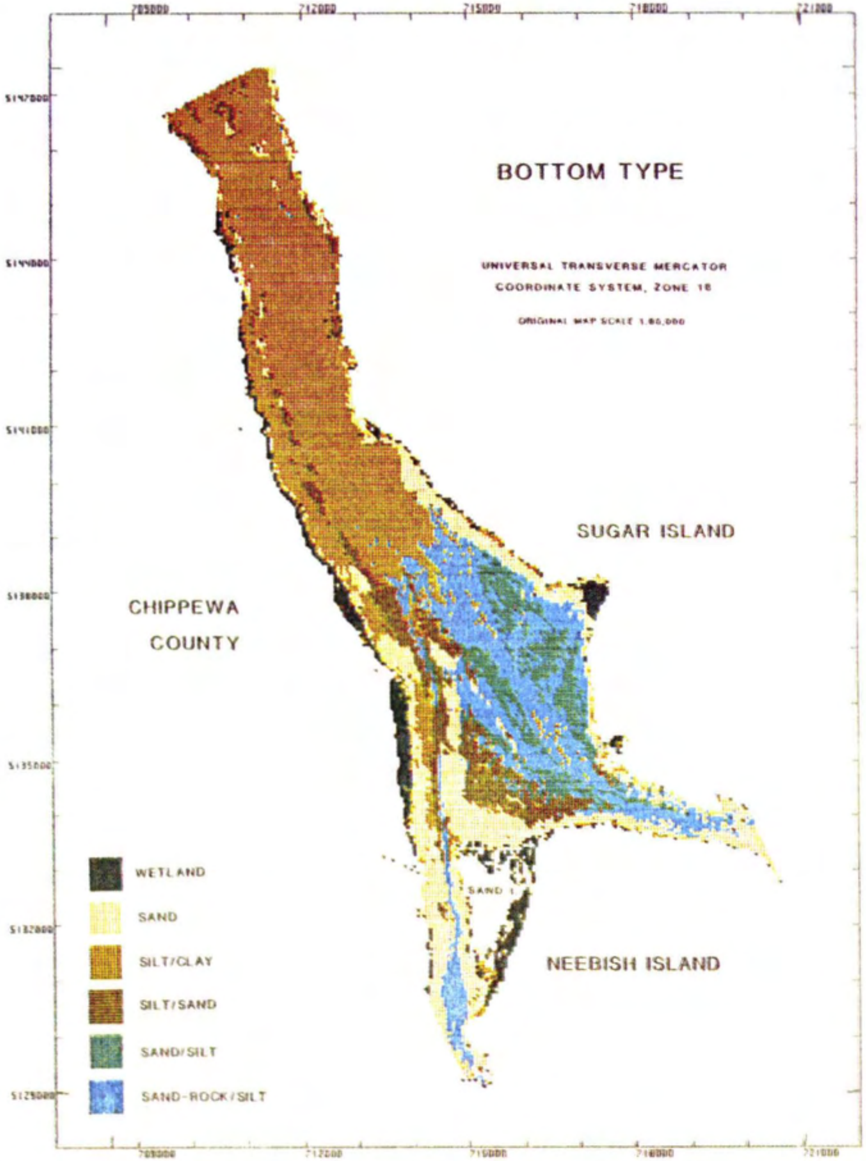

PLATE 2. Thematic map of water depth classes.

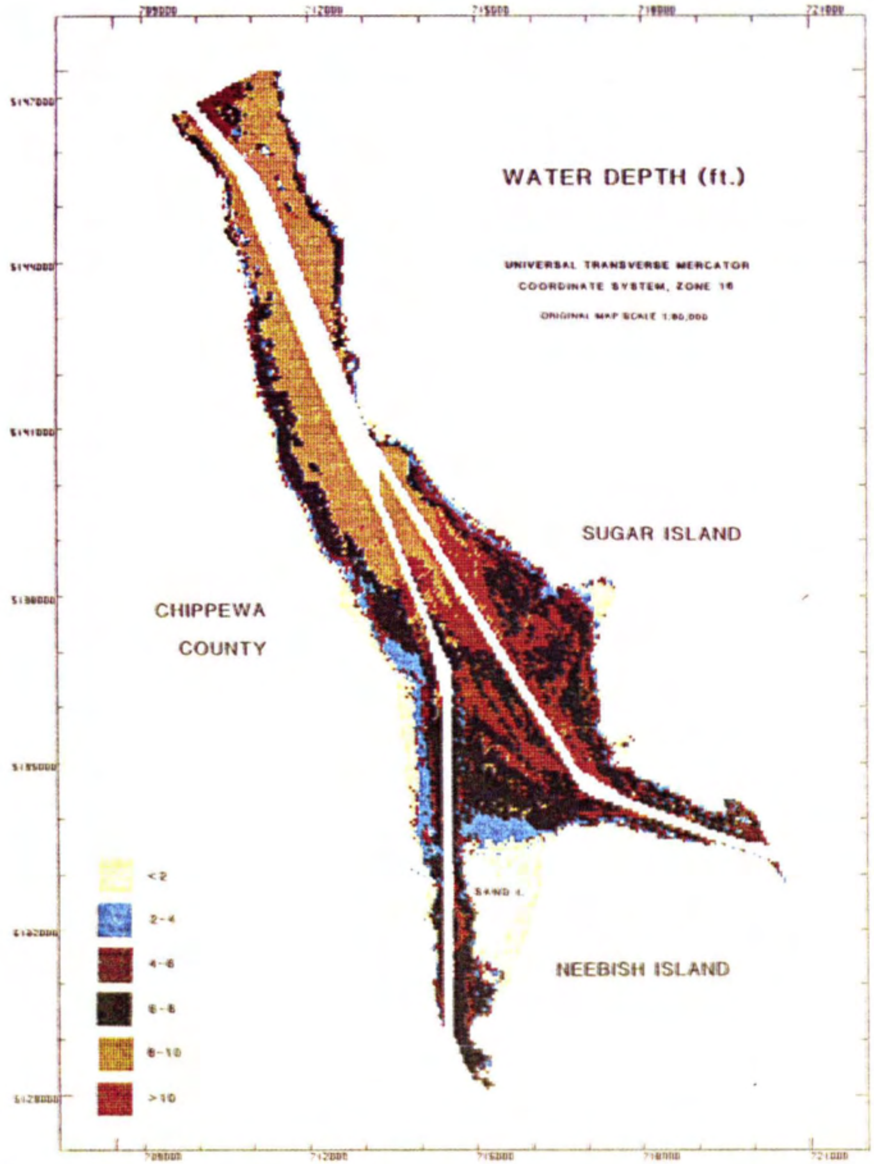

PLATE 1. Thematic map of river bottom types.

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